FIRST APPLICATION OF THE HUYGENS DESCENT TRAJECTORY WORKING GROUP TRAJECTORY RECONSTRUCTION ALGORITHM TO HUYGENS DATA

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ABSTRACT

The ESA Huygens probe performed a successful Entry, Descent, and Landing (EDL) sequence through Titan's dense atmosphere on January 14, 2005. During all three phases, i.e., the supersonic entry phase, the descent phase, as well as the impact and post impact phases, the probe performed measurements that were used for the reconstruction of its entry and descent trajectory.

We first discuss the datasets relevant to the entry and descent trajectory reconstruction. We then provide an overview of the reconstruction strategy, and show preliminary results of the reconstructed entry and descent trajectory, including both position and velocity.

Key words: Huygens mission, trajectory reconstruction.

1. INTRODUCTION

1.1. Huygens Mission Description

The Huygens Probe is the ESA-provided element of the joint NASA/ESA/ASI Cassini/Huygens mission to Saturn and Titan (Lebreton and Matson, 2002). Cassini/Huygens was launched on October 15, 1997 and arrived at Saturn on July 1, 2004. Following two orbits of Saturn, the Huygens Probe was released on December 25, 2004 and reached Titan on January 14, 2005.

The Huygens probe was equipped with six instruments. Throughout the descent and onto the surface, the Huygens instruments performed scientific measurements of the physical and chemical properties of Titan's atmosphere, include atmospheric and haze composition, pressure, temperature, and winds.

1.2. Probe Entry, Descent, and Landing Sequence

The Huygens probe entry and descent sequence is schematically shown in Fig. 1. The probe was protected from the atmospheric induced radiative and convective heat fluxes during entry by a 2.75 meter diameter front heat-shield as it decelerated from about Mach 22.5 to Mach 1.5 in just under five minutes (Clausen *et al.*, 2002). Approximately 4.45 minutes after the entry the probe speed decreased to Mach 1.5 and the probe Central Acceleration Sensor Unit (CASU) measured the deceleration threshold of 10 m/s^2 (on the trailing edge of the deceleration pulse) designated as S_0.

The descent of the probe through Titan's atmosphere was controlled by three parachutes (pilot, main, and stabilizing drogue chute). The correct instant for parachute deployment (mission time event T_0) was determined by the probe on-board computers that processed the measured values of the accelerometers, which monitored the probe deceleration as an indicator of Mach number. At T_0=S_0+6.375 seconds (UTC 09:10:21[1]) the pyrotechnic devices fired a mortar, which pulled out the pilot chute, a 2.59 m disk gap band (DGB) type parachute. 2.5 seconds later the probe back cover was released and the 8.3 meter main DGB parachute was then deployed. This sequence of events occurred at Mach 1.5 and an altitude of about 155 km. The heat-shield was separated at T_0+32.5 seconds and about 17.5 seconds later (to ensure that the shield was sufficiently far below the probe to avoid possible instrument contamination) the inlet ports of the probe Gas Chromatograph/Mass Spectrometer and Aerosol Collector and Pyrolyser instruments were opened. The Huygens

[1]The currently best estimate can be determined within an 0.6 second time window of UTC 09:10:20.3 to 09:10:20.9 (Couzin, 2005).

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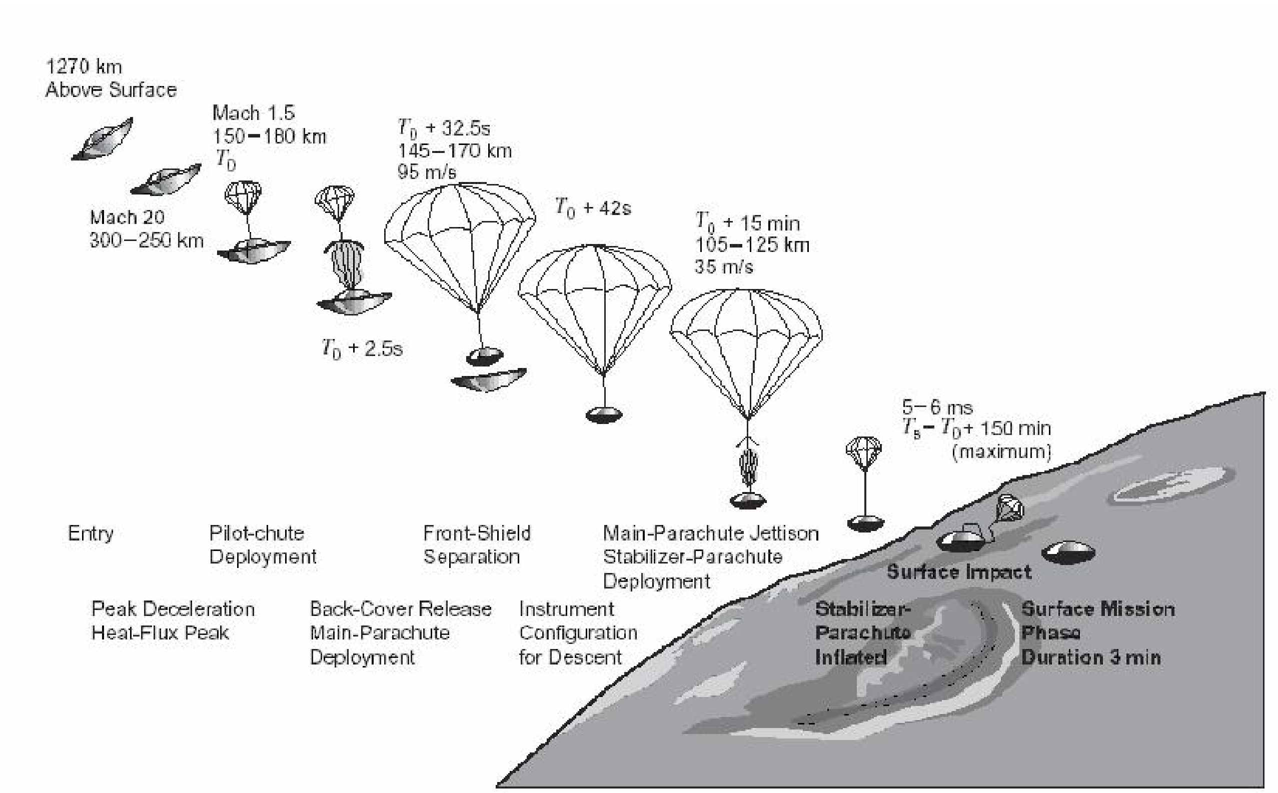

Figure 1. The Huygens probe entry and descent mission sequence;

antennas started to transmit at T_0+45 seconds (UTC 09:11:06). As telemetry could not be transmitted by the probe during the entry phase until back cover removal, a limited set of engineering housekeeping data and the HASI entry science accelerometer data, was stored on board the probe for delayed transmission to Cassini after the radio link was established.

The probe descended beneath the main parachute for 15 minutes, at which time the main parachute was released and a 3.03 meter drogue parachute was deployed to carry the probe to Titan's surface. The duration of the descent following the T_0 event was 2 hours 27 minutes and 50 seconds (Lebreton *et al.*, 2005). Throughout the descent to the surface as Huygens measured the chemical, meteorological, and dynamical properties of the Titan atmosphere, the experiment and housekeeping/engineering data was transmitted to the orbiter at 8 kbit/s.

1.3. The Huygens Descent Trajectory Working Group

The responsibility of reconstructing the Huygens entry and descent trajectory from the the 1270 km interface altitude to the surface is given to the Huygens Descent Trajectory Working Group (DTWG), chartered in 1996 as a subgroup of the Huygens Science Working Team (HSWT) (Atkinson *et al.*, 2005). The DTWG membership comprises the Huygens and Cassini project scientists, the Huygens Operations Scientist, representatives from each of the probe science instrument teams and contributing orbiter teams, and industry. The primary purpose of the Descent Trajectory Working Group is to provide a single, common descent profile that is consistent with all the available probe and orbiter engineering and science data, and that can be utilized by each instrument team for analysis of experiment measurements, and correlation of results between experiments.

1.4. Data Sets used for the Entry, Descent, and Landing Reconstruction

To perform the entry and descent trajectory retrieval, a dedicated tool was developed (Kazeminejad, 2005), which is described in more detail in Sec. 2. The reconstruction effort utilized the following datasets:

- **Cassini Navigation Data**: the Cassini NAV team provided to the DTWG the probe state vector at the *interface epoch* (i.e., UTC 2005-01-14T09:05:52.53).
- **Huygens Atmospheric Structure Instrument (HASI)**: spacecraft acceleration measurements during the entry phase, measurement of atmospheric properties (i.e, pressure, temperature, and electric properties) during the descent phase (Fulchignoni *et al.*, 2002, 2005);

- **Doppler Wind Experiment (DWE)**: measurement of zonal wind speeds during the descent phase (Bird *et al.*, 2002, 2005);

- **Gas Chromatograph and Mass Spectrometer (GCMS)**: measurement of atmospheric composition and mole fraction of major constituents (Niemann *et al.*, 2002, 2005);

- **Surface Science Package (SSP)**: measurement of probe impact time (Zarnecki *et al.*, 2002, 2005);

- **Probe Housekeeping Measurements**: timing of major events in the sequence, altitude measurements from radar altimeter units (Lebreton *et al.*, 2005).

- Huygens was equipped with two **Radar Altimeter Units (RAU)** operating as unit A (15.4 to 15.43 GHz) and unit B (15.8 to 15.83 GHz). It is important to note that the RAUs were part of the probe Command and Data Management Subsystem and cross-strapped to both of the two totally redundant CMDUs. This implied that despite the loss of channel A (see explanation later in the text) both digital RAU signals are available. An extensive postprocessing of the RAU data necessary in order to correct the raw data for various errors (i.e., digital, altitude, and temperature errors) (Trautner, 2005). The calibration provided a relative (1σ) error bar of 2.7 %.

All of the aforementioned data sets were available and utilized in the entry and descent trajectory retrieval as planned, with the sole exception being the Doppler Wind data for zonal wind drift retrieval. The Doppler Wind Experiment relied on accurate measurements of the Huygens Channel A carrier frequency. Channel A utilized ultrastable oscillators (USO) on the probe for the accurate generation of a stable carrier frequency, and an ultrastable oscillator on the Cassini orbiter for measurement of small Doppler-induced drifts in the telemetry frequency. From these frequency drifts the probe zonal wind-induced motions could be retrieved. However, due to a missing telecommand to provide power to the orbiter USO, all Huygens Channel A data was lost and the orbiter-based Doppler wind measurement could not be made. Fortuitously, the Channel A carrier was detected at Earth using a planet-wide array of radio telescopes and the measurement of the zonal winds was still achieved, albeit with a somewhat lower time and altitude resolution than originally planned.

2. THE DTWG TRAJECTORY RECONSTRUCTION TOOL

The DTWG Trajectory Reconstruction Tool (Kazeminejad, 2005; Kazeminejad and Atkinson, 2004) was developed at the Space Research Institute of the Austrian Academy of Sciences (Graz/Austria) under contract with the Research and Scientific Support Department of ESA for the purpose of reconstructing the Huygens probe entry and descent trajectory and attitude (i.e., the angle-of-attack history) during the entry phase. The tool uses the NAIF Spice toolkit and was developed in a "multi-planet" mode so that it can be easily adapted for other probe missions to any other solar system planet.

The reconstruction strategy consists of the following phases:

1. **Entry Phase**: this phase comprises the reconstruction of the probe altitude and descent speed profiles, and the physical properties of the upper atmosphere including density, pressure, and temperature from the interface altitude[2] to the initiation of the parachute sequence at $\sim$ 160 km). The sole dataset used during this phase was from the probe accelerometer;

2. **Descent Phase**: this phase comprises the reconstruction of the probe vertical movement, i.e., altitude and descent speed from measured atmospheric temperature, pressure, and molecular mass as well as the probe horizontal movement, i.e., drift in longitude and latitude as derived from the zonal wind measurements of the Doppler Wind Experiment. Note that the probe latitude is kept constant in the reconstruction of the entire descent phase. This can be justified by the assumption of weak and negligible meridional winds. The descent altitude profile was independently and directly measured by the two redundant radar altimeter units in the altitude range of 45 km down to about 130 m. A radar descent speed profile in the same altitude range can easily be derived by calculation of the time derivative.

3. **Trajectory Fitting Phase**: this phase allows an adjustment of the initial state vector at interface altitude in order to achieve an optimum "match" of the entry and descent phases by adjusting the probe initial conditions at interface altitude using a classical weighted linear least-squares fitting algorithm.

3. ENTRY PHASE RECONSTRUCTION

The entry phase is reconstructed by a numerical integration of the equations of motion which are outlined in detail in Kazeminejad (2005); Kazeminejad

[2]The interface altitude is defined as 1270 km above Titan's reference surface and represents the official NASA/ESA handoff point where the probe initial state vector and its uncertainties (the covariance matrix) are provided by the Cassini Navigation team to ESA.

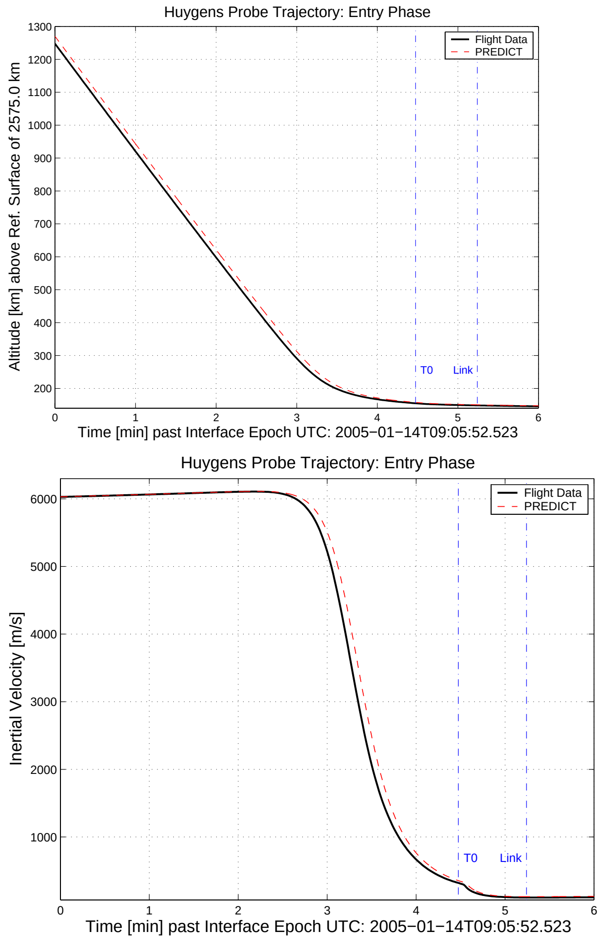

Figure 2. Altitude (upper panel) and inertial velocity (lower panel) profile of the HASI servo accelerometer based entry phase reconstruction.

and Atkinson (2004). The combination of the following data was used for the entry phase reconstruction effort:

- The Huygens probe state vector and uncertainties at interface epoch and a variety of planetary constants (e.g., Titan GM, Titan radius, planetary rotation rate, etc.) provided to the DTWG tool in the form of a NAIF text kernel.
- The axial probe deceleration as measured by the HASI X-Servo accelerometer;
- The reconstruction algorithm calculated the gravitational field of Titan as the primary body and Saturn and the Sun as two perturbing bodies. No flattening of the primary body was taken into account for this simulation.

4. DESCENT PHASE RECONSTRUCTION

The probe descent phase trajectory was reconstructed from the following datasets:

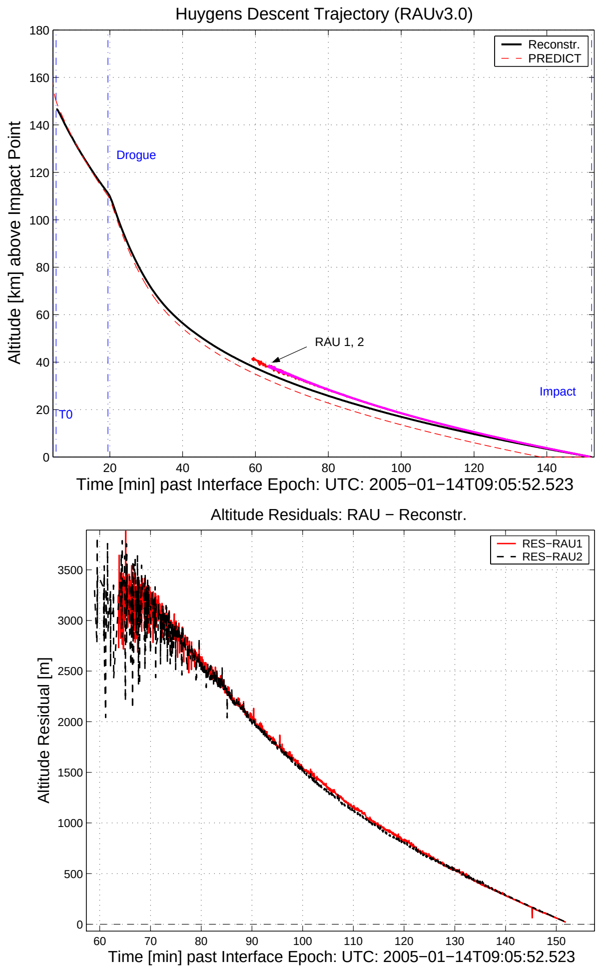

Figure 3. Upper panel: reconstructed altitude profile based on the HASI P and T, GCMS mole fraction, and SSP impact epoch measurements (solid line) compared to the preflight trajectory simulation (dashed line) (Kazeminejad et al.*, 2004; Pérez-Ayúcar* et al.*, 2005). Furthermore the calibrated measurements of the two RAU are shown. Lower panel: altitude residuals of the RAU and the reconstructed altitude profiles.*

- The pressure and temperature measurements from the HASI instrument in combination with the GCMS measurements of the mole fractions (needed to infer the mean molecular mass of the gas mixture) of the major atmospheric constituents to derive altitude and descent speed;
- the DWE zonal wind measurements to derive the probe longitude drift and impact coordinates;
- the SSP penetrometer accelerometer measurements at probe surface impact in order to constrain the probe impact time;
- the SSP sounder-derived altitude; and
- the two RAU altitude measurements to derive the surface elevation in the final part of the descent phase (~45 km down to 130 m);

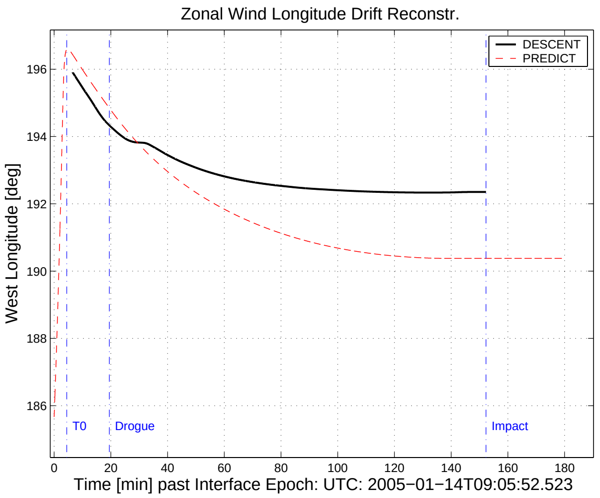

Figure 4. Huygens longitude drift based on the measured DWE zonal wind speed profile (solid line). In addition the preflight simulation [based on the HRTF simulated zonal wind profile (Lebreton, 2001)] is represented by the dashed line.

The descent phase reconstruction was done in the so called "reverse" mode, i.e., starting from the probe impact time upwards.

5. ENTRY/DESCENT PHASE MERGING STRATEGY

The Huygens entry phase trajectory required as an essential input the probe state vector. Due to the comparatively high uncertainties (up to 30 km 1σ radial uncertainty) a methodology was developed to adjust and correct the initial state vector based on two objectives:

- to achieve a better consistency of the probe position and velocity vector with measured probe acceleration.
- to achieve a better merging of the accelerometer based entry phase trajectory with the atmospheric measurement based descent phase trajectory in both altitude and descent speed.

The methodology applied here was based on a least-squares fitting algorithm, which took into account the *a priori* covariance matrix of the state vector. The mathematical formulation of the algorithm is provided in detail in Kazeminejad (2005) and required the propagation of the system transition matrix together with the state vector. A total of 42 first order differential equations (6 for the state vector and 36 for the state transition matrix) had therefore to be propagated from the interface epoch down to an altitude of ~100 km. In the overlapping region of the entry and descent phase the residuals in altitude and descent speed were calculated and used for the adjustment of the state vector at interface epoch.

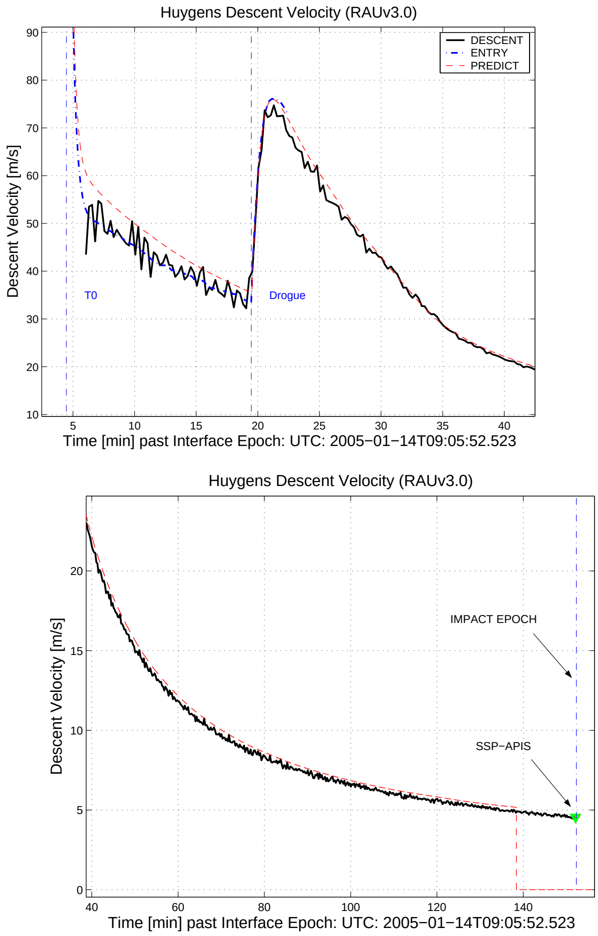

Figure 5. Huygens descent speed profile during the first portion (upper panel) and final portion (lower part) of the descent phase. In the upper panel the dashed-dotted line (labeled "ENTRY") shows the accelerometer based reconstruction. The solid line (labeled "DESCENT") shows the descent speed profile as reconstructed from the atmospheric measurements, and the dashed line shows the results of the preflight simulation. The triangle in the lower panel represents the descent speed derived from the SSP acoustic sounder measurements.

6. DISCUSSION OF RESULTS

The results of the entry phase trajectory reconstruction are depicted in Fig. 2. The upper panel shows the altitude profile with respect to the reference surface of 2575 km distance to Titan's center. One can see that at the interface epoch the probe position was actually 22 km closer (i.e., at a reference surface altitude of about 1248 km) to the planet's center than predicted by the Cassini Navigation team (this vector was also used for the preflight simulation trajectory, which was labeled as "PREDICT" in this plot). This corresponds to ~0.72 σ of the specified radial error. The lower panel shows the norm of the inertial velocity vector. One can clearly see that the inertial entry velocity was very close to the predicted 6 km/s. The two vertical dashed lines show the times of the start of the parachute sequence (T_0) and the start of transmission (designated as "Link").

The upper panel of Fig. 3 compares the reconstructed probe altitude (solid line) with the preflight simulation (dashed line). Furthermore the Radar Altimeter Unit (RAU) measured altitude profiles are shown (arrowed with "RAU 1, 2"). The residual between the reconstructed and RAU altitude profiles are plotted in the lower panel of Fig. 3. One can see that the residuals increase from a few meters close to the surface up to more than 3.5 km at an altitude of 60 km. A dedicated parameter study showed that this discrepancy is most likely to a systematic measurement error of the RAU, which provide altitude and descent speed measurement that are too high. The descent phase reconstruction clearly shows that the preflight entry and descent simulations (Kazeminejad *et al.*, 2004) predicted a probe impact time that occurred about 14 minutes too early. This is partially due to the uncertainties in the main and drogue chute aerodynamic database.

The results of the longitude drift integration based on the measured DWE zonal wind speed profile is depicted in Fig. 4 The longitude drift integration was initiated at $T0{+}121.5$ sec (= interface epoch + 6.5 min) sec, which corresponds to an altitude of $\sim$143.9 km. At this point the initial latitude and west longitude values of respectively 10.34 deg and 195.91 deg were assumed, which are based on the results of the entry phase (accelerometer based) trajectory reconstruction. It is important to note that the latitude value was kept constant and only the longitude drift was integrated. This is based on the assumption of zero meridional winds, consistent with the DWE retrieval algorithm (Dutta-Roy and Bird, 2004). The end point of the longitude drift integration provides an estimated impact (west) longitude value of 192.35 deg. Taking into account the uncertainties of the zonal wind measurements the estimated impact point coordinates can be summarized as (192.35 ± 0.24) deg WLon and (10.34 ± 0.17) deg SLat.

The reconstructed descent speed profile is shown in Fig. 5. The upper panel shows the first portion of the descent phase (i.e., descent under main chute and first 20 minutes of drogue chute descent). In addition to the atmospheric measurement based descent phase reconstruction (labeled as "DESCENT'), the descent speed profile of the entry phase (accelerometer based) reconstruction is depicted (thick dash-dotted line labeled as "ENTRY"). Comparing the reconstructed descent speed profiles under the main chute (portion between the two vertical dashed lines, labeled as "T0" and "DROGUE") to the preflight simulation, one can see that the descent speed is about 5 m/s lower than the prediction. This also explains the later impact time than expected. The lower panel of Fig. 5 shows the final part of the descent speed up to the impact on the surface, which was measured very accurately by the SSP impact penetrometer (SSP-ACCI).

In the last 90 m prior to impact, the SSP acoustic sounder (SSP-APIS) provided 6 altitude measurements, which were used to derive an impact speed of about 4.6 m/s (shown as triangle in the lower panel of Fig. 5). This value is consistent with the reconstructed descent speed profile based on atmospheric measurements.

7. CONCLUDING REMARKS

The Huygens probe mission provided a variety of high quality data that contain useful and essential information on the probe's entry and descent trajectory. Within the framework of the Huygens Descent Trajectory Working Group, a dedicated tool was developed to reconstruct the trajectory based on the probe measurements. The DTWG tool was extensively tested prior to the mission using simulated probe data (Pérez-Ayúcar *et al.*, 2004, 2005) and was now for the first time applied to the real data set. Preliminary results were presented in this paper showing the reconstructed altitude and descent speed profiles during both the hyper and supersonic entry phase and the descent phase under the main and drogue parachutes. The entry and descent phase merging algorithm was applied to adjust the initial conditions provided by the Cassini Navigation team within their stated uncertainties. The adjusted initial conditions ensure a smooth and accurate transition between the two independent entry and descent phase reconstruction efforts, which both are based on different and independent datasets. The reconstruction effort is still work in progress and more detailed analysis and reconstruction results will be provided in the upcoming months.

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